Cosmology II: The CMB, dark matter and dark energy

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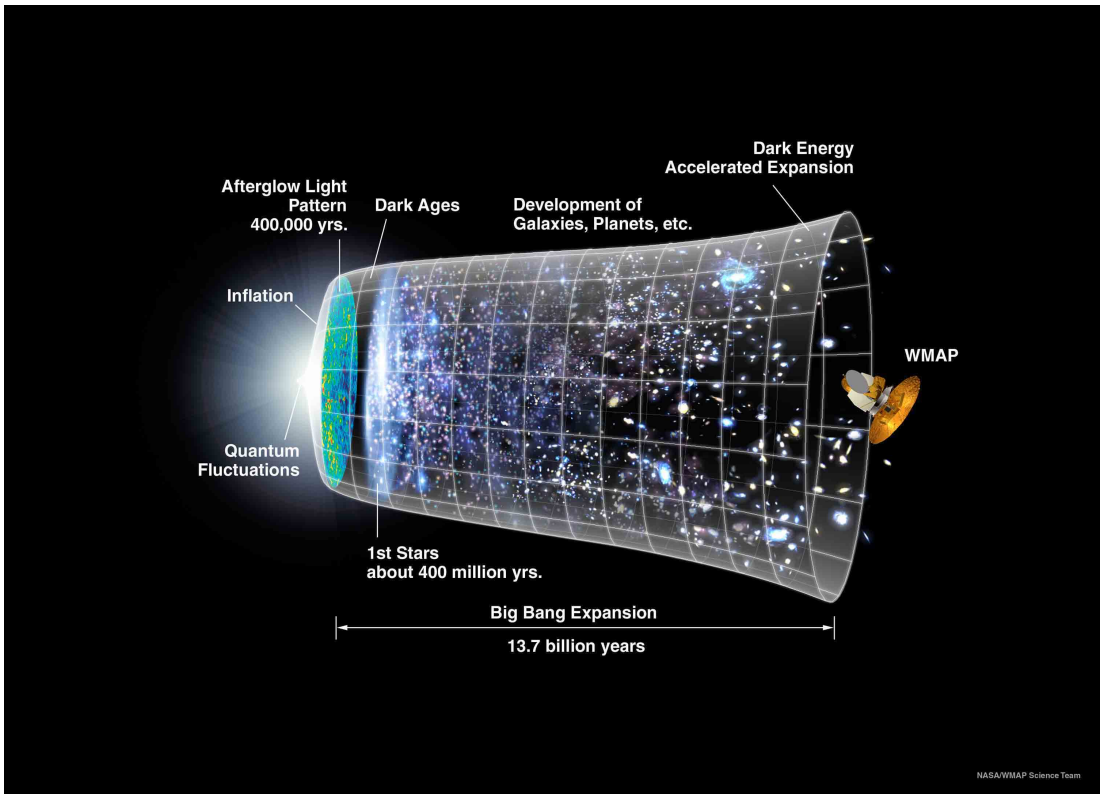
Thermal history

In the past the Universe was not only much denser than today but also much hotter.



Age of the Universe: $t_0 \simeq 13.7$ billion years

The most remarkable events of the hot Universe:

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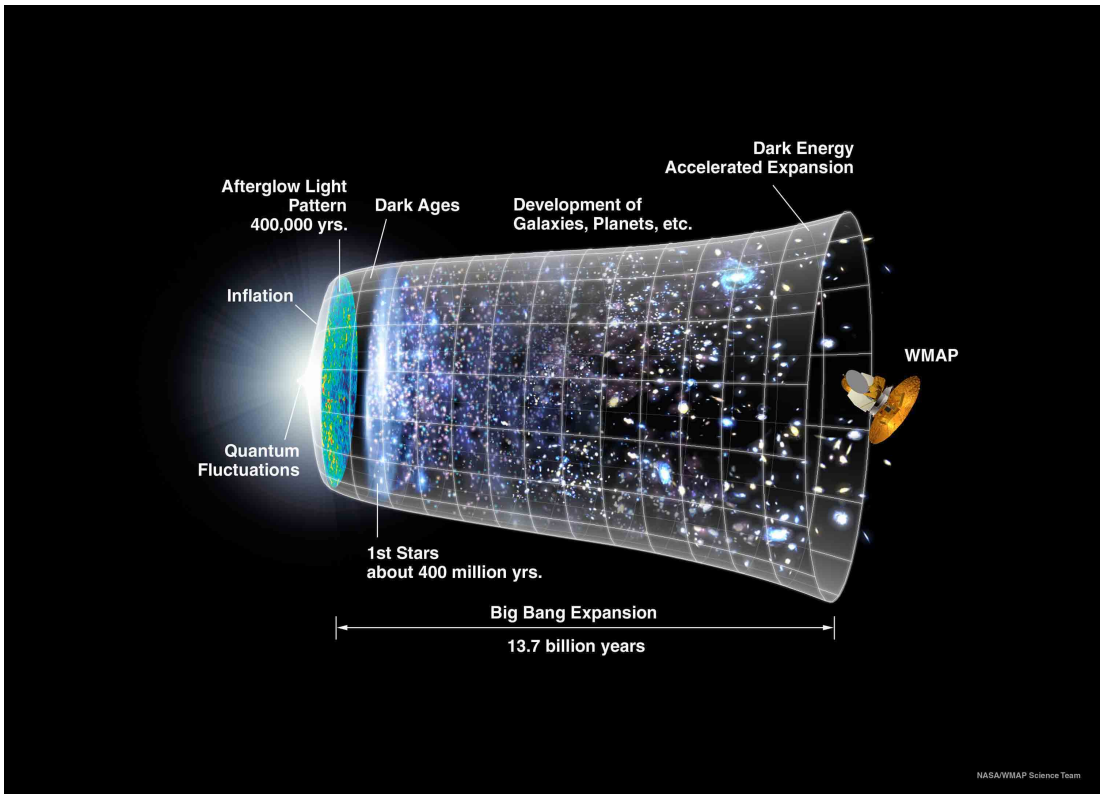

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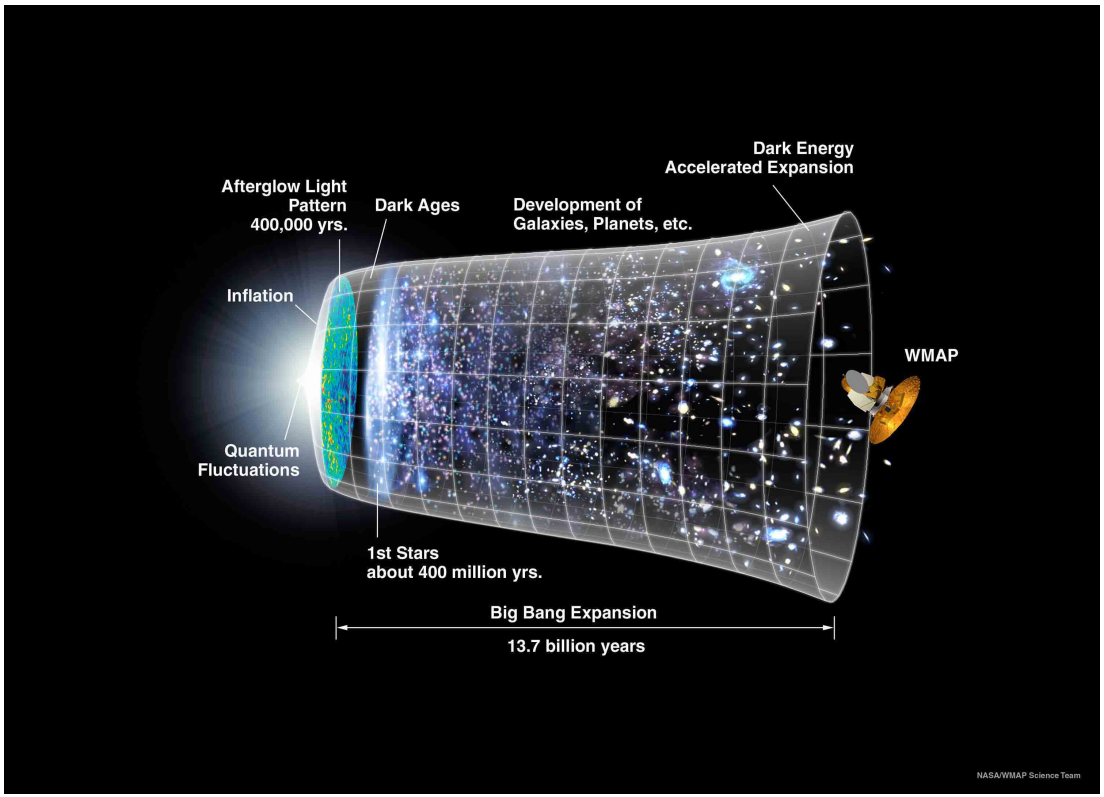

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- Inflation ?

Recombination

- Since the photon (radiation) energy density scales like $T^4 \propto a^{-4} \propto (z+1)^4$ while the matter density scales like $mn \propto a^{-3} \propto (z+1)^3$, at very early time, the Universe is radiation dominated ($z \gtrsim 3000$, $t \lesssim 10^4$ years).

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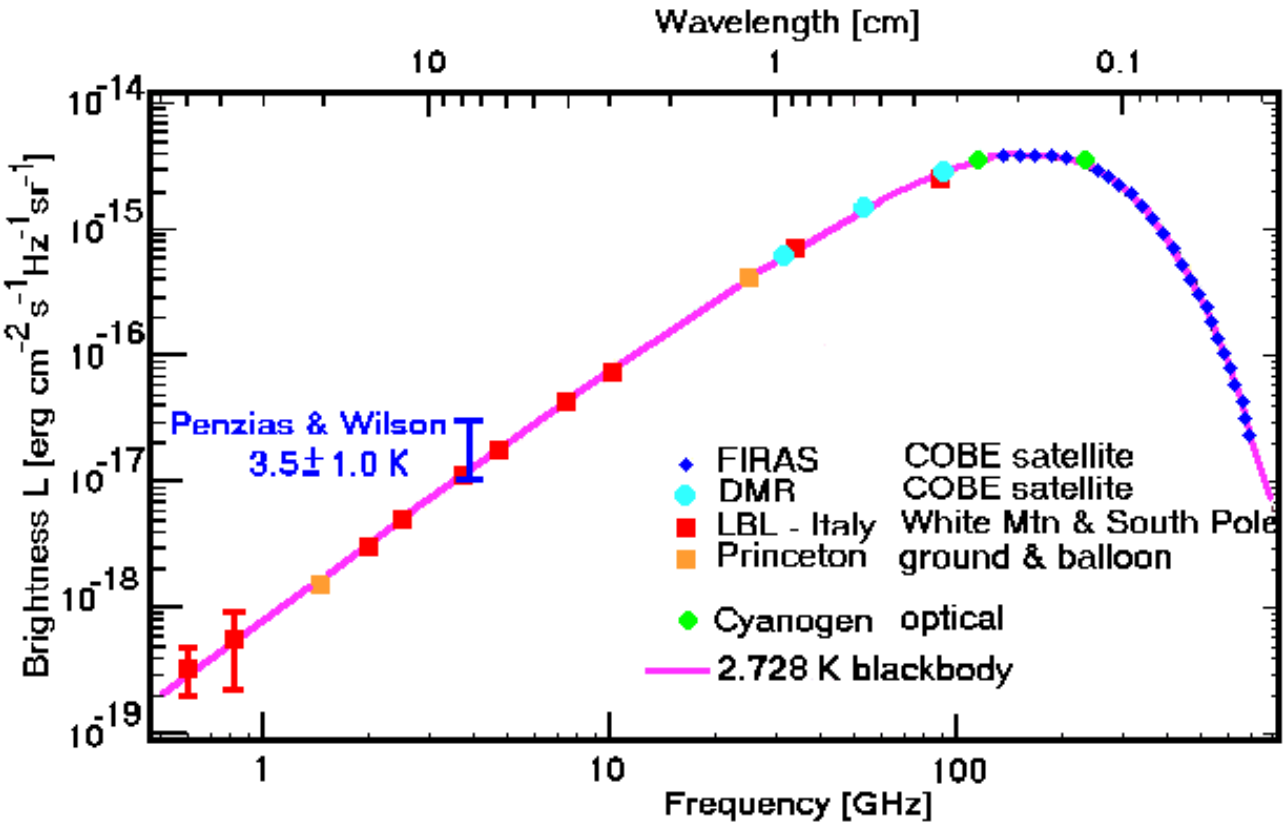
- It represents a 'photo' of the Universe when it was about 300'000 years young, corresponding to a redshift of $z \simeq 1100$.

The cosmic microwave background: the spectrum

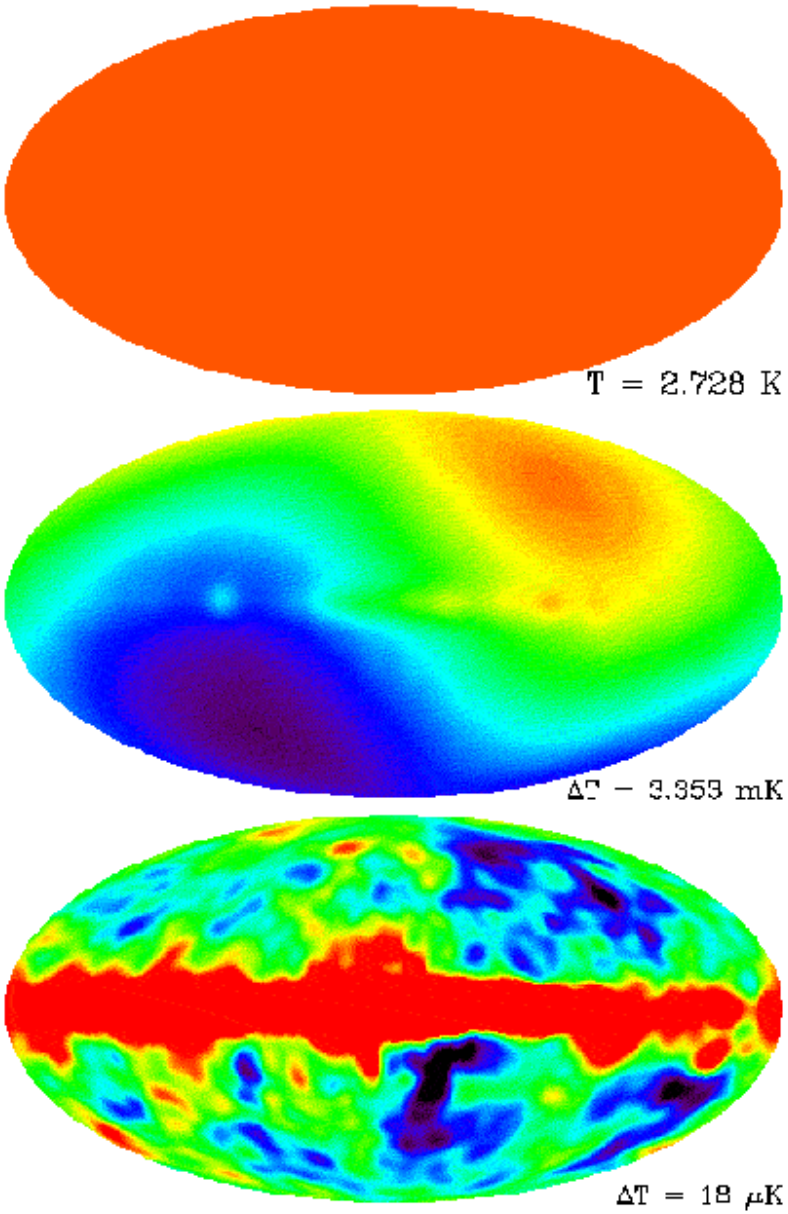


(Fixen et al. 1996)

Nobel Prize 1978 for Penzias and Wilson,
Nobel Prize 2006 for Mather

$$T_0 = 2.728\text{K} \simeq -270.5^o\text{C}$$

The cosmic microwave background: anisotropies



Map of the CMB temperature: perfectly isotropic.

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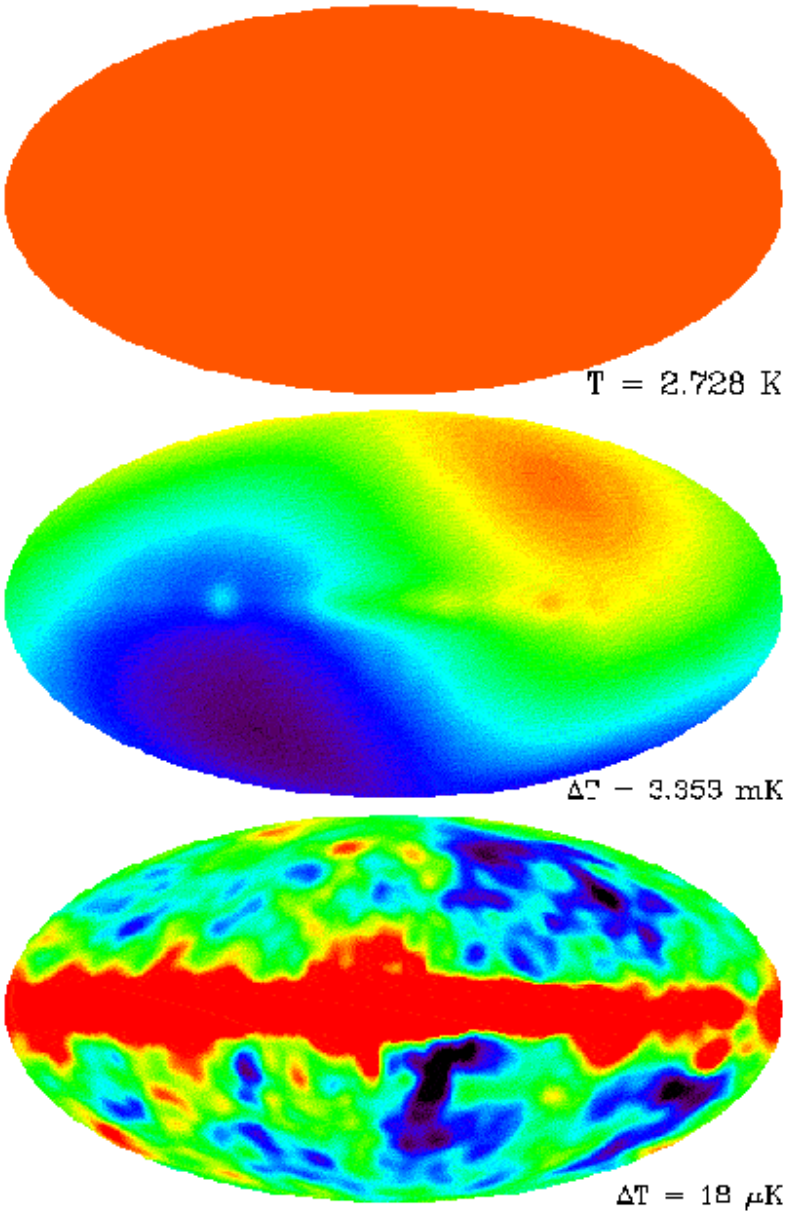

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Subtracting the monopole a dipole of amplitude $\sim 10^{-3}$ becomes visible. It is mainly due to the motion of the solar system with respect of the sphere of emission (last scattering surface).

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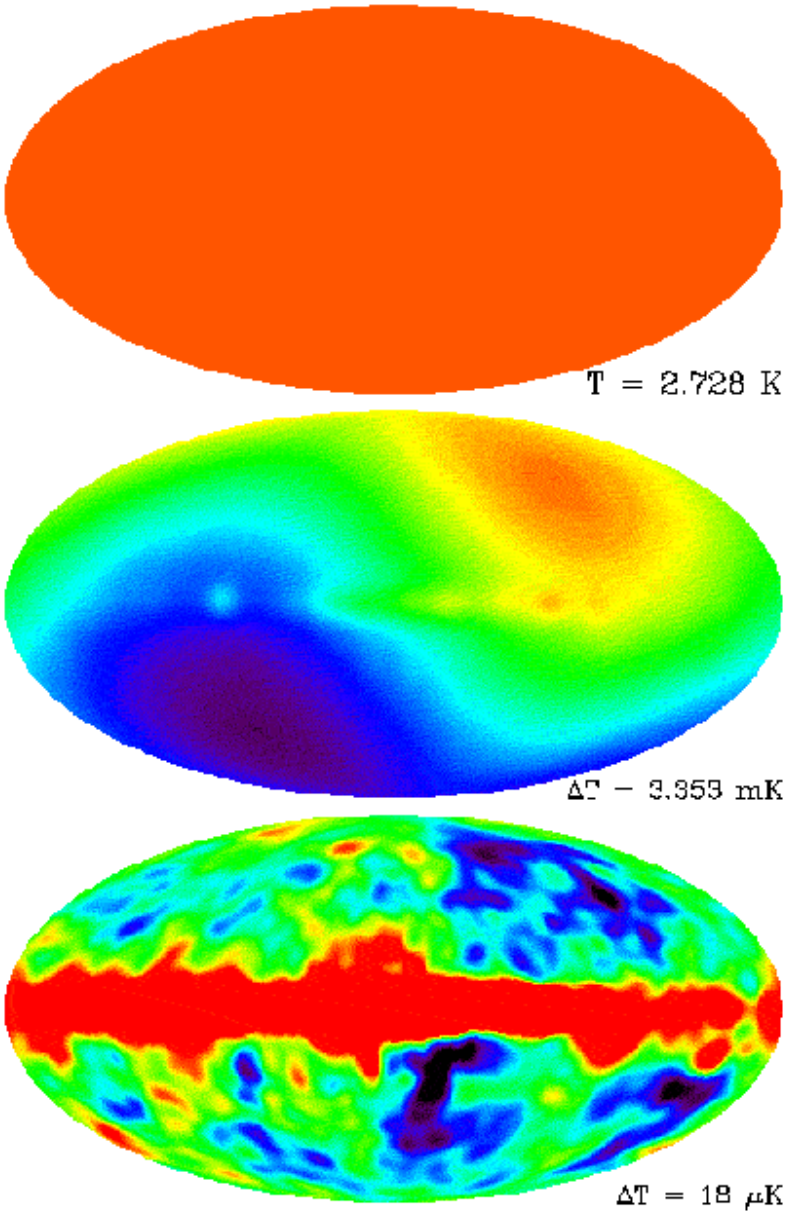

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And what is this? Left over after subtracting the dipole. Fluctuations of amplitude $\sim 10^{-5}$.

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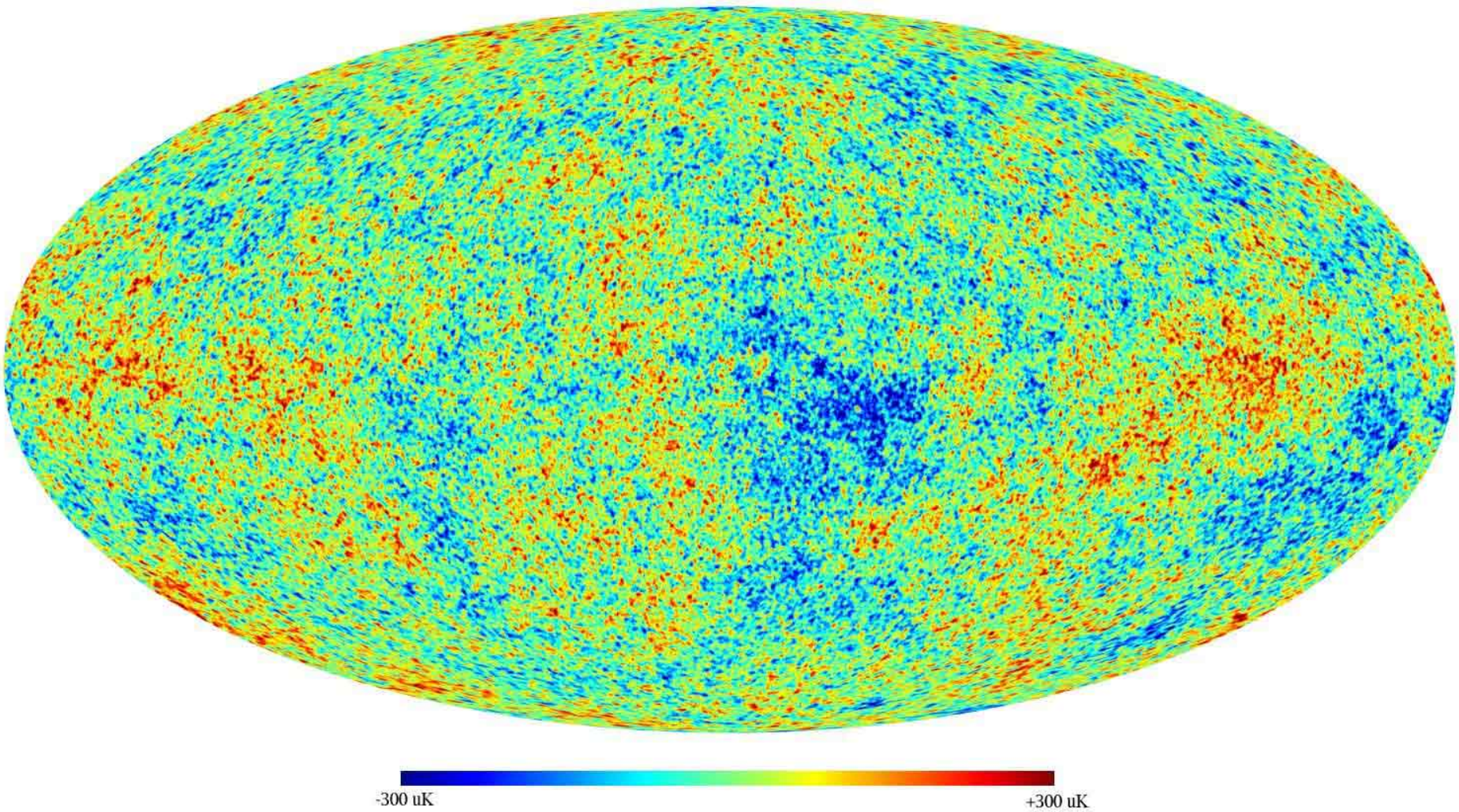

ESA/Planck (2015)

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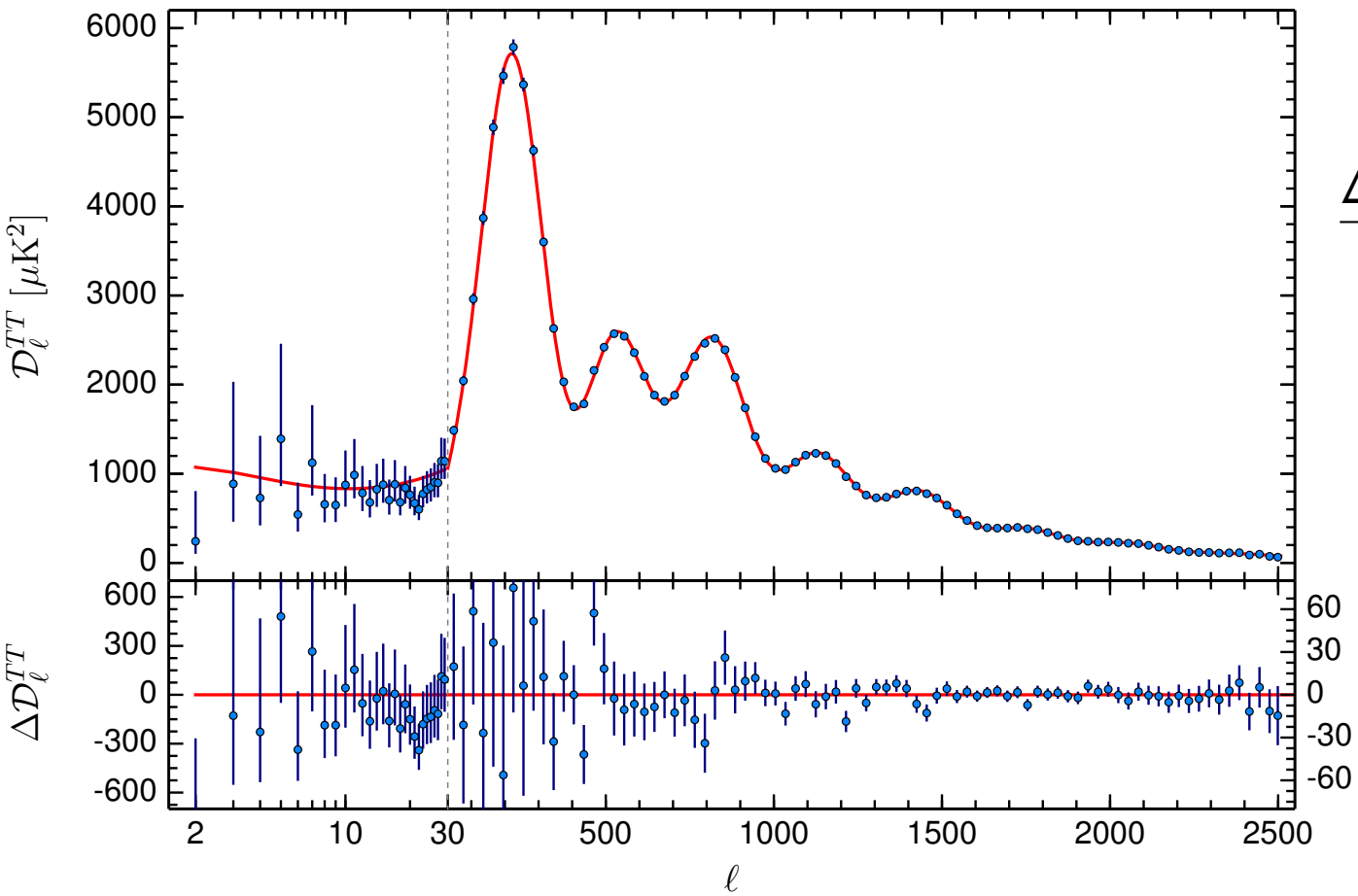


$$\frac{\Delta T}{T}(\mathbf{n}) = \sum a_{\ell m} Y_{\ell m}(\mathbf{n})$$

$$C_\ell = \langle |a_{\ell m}|^2 \rangle$$

$$\mathcal{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$

$$\frac{\Delta T}{T} \simeq 2 \times 10^{-5}$$

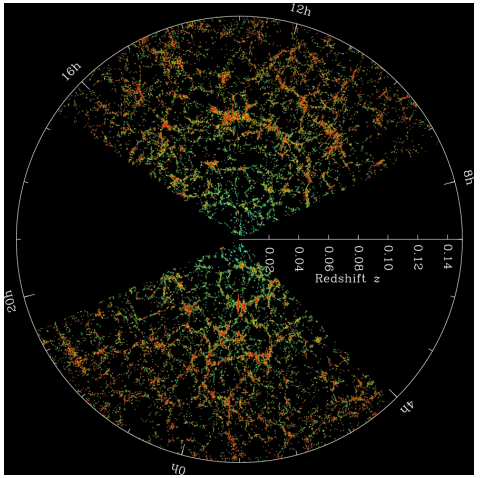
ESA/Planck (2015)

$\ell = 200$ corresponds to about 1^o. $\Rightarrow$ 'acoustic' peaks. $(\theta \simeq 180^o/\ell)$

(This is roughly the double of the angular size of the full moon (or of the sun).)

The cosmic microwave background: anisotropies

The matter distribution in the observed Universe is not very homogeneous and isotropic. It is in form of galaxies, clusters, filaments, voids.
The idea is that these large scale structures formed by gravitational instability from small initial fluctuations which have been set up very early in the Universe (during inflation).



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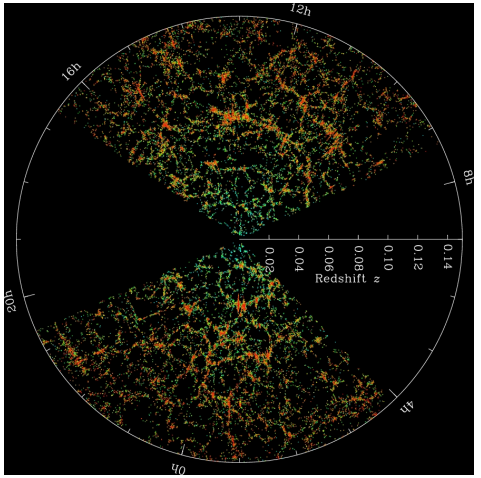

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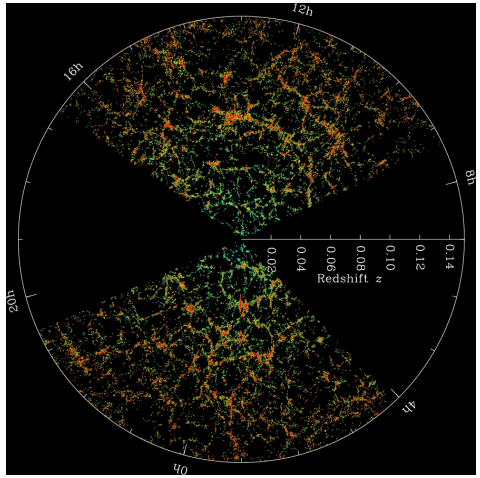

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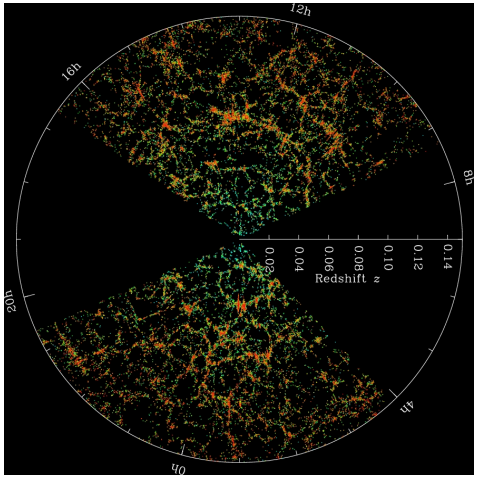

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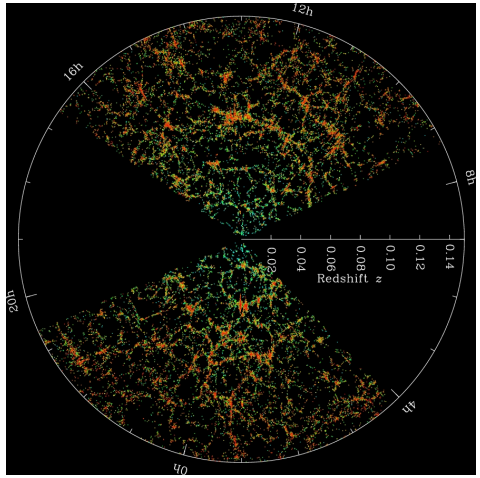

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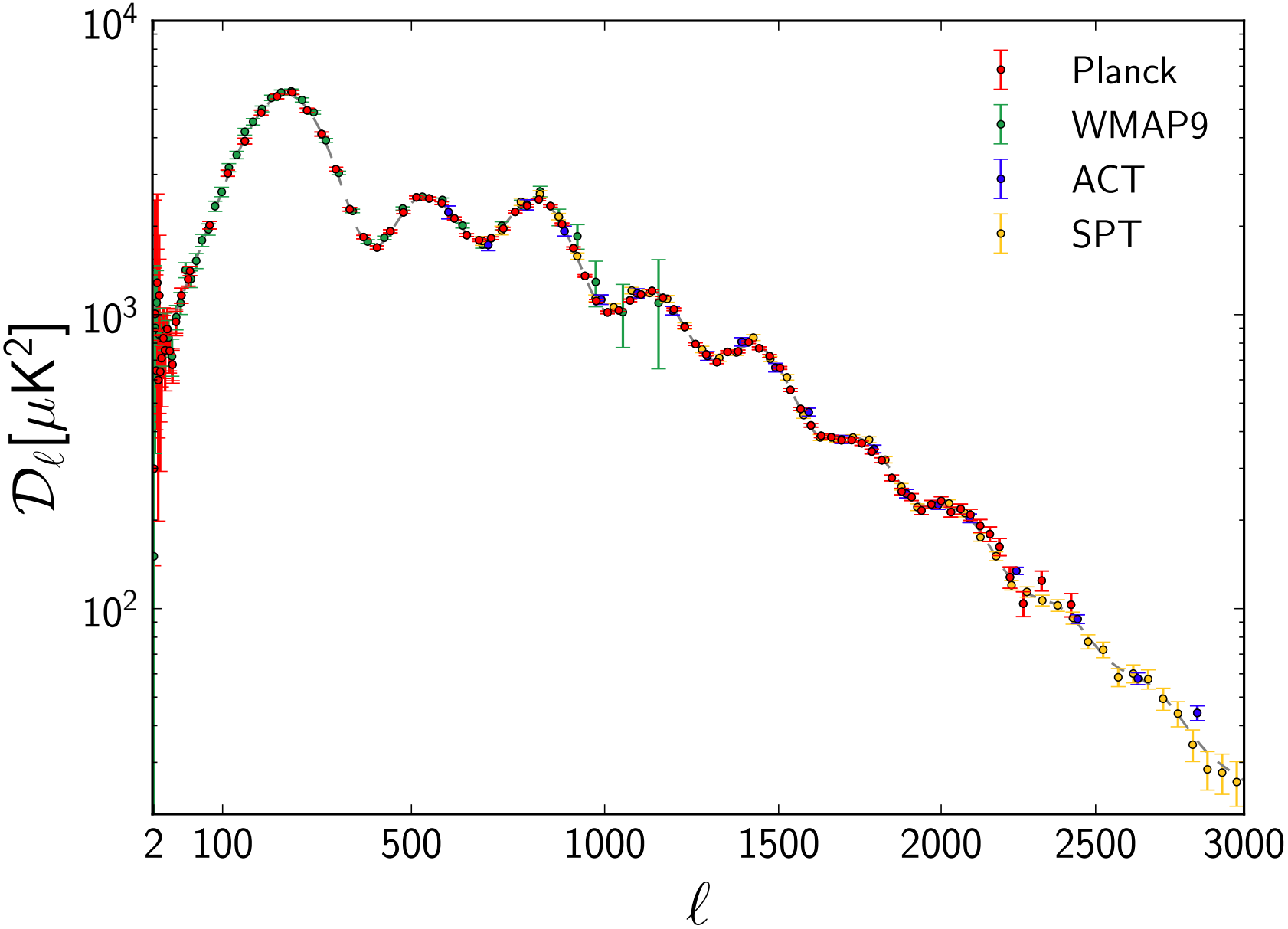
- The second peak peak corresponds to fluctuations which have had time to make exactly 1 contraction and 1 expansion since horizon entry until decoupling (under density).
- The third peak corresponds to fluctuations which have had time to make exactly 2 contractions (and 1 expansion) since horizon entry until decoupling. $\cdots$

Combined CMB data



The cosmic microwave background: parameters from Planck (2015)

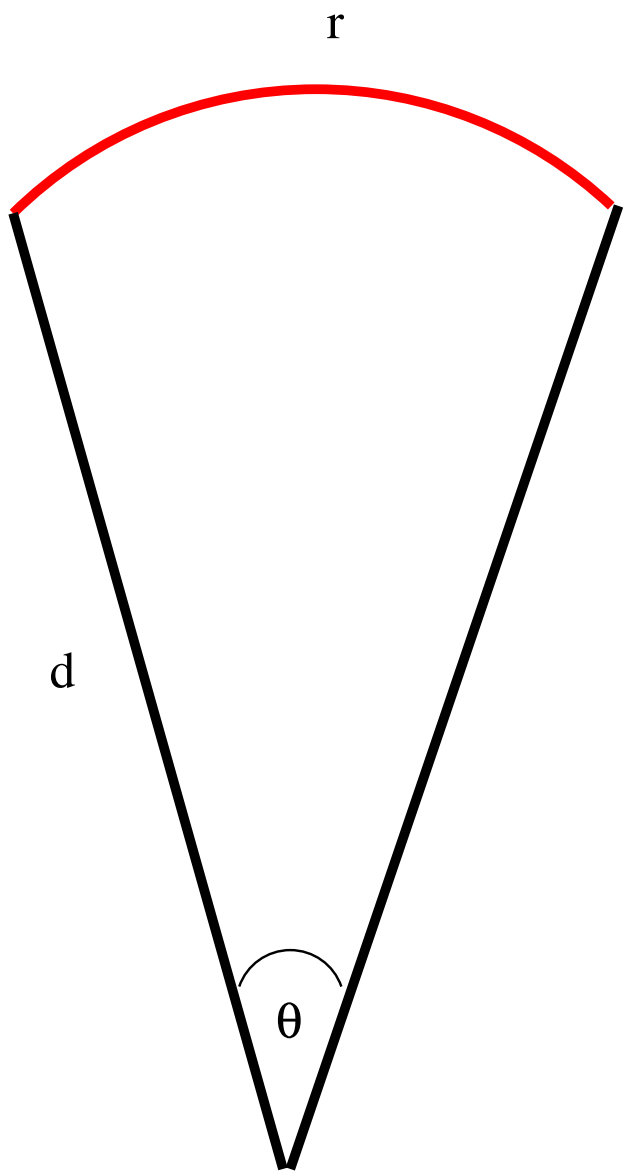
The patches of peak amplitude temperature fluctuations are standard rulers. Their size is given by the age of the Universe at the time of decoupling (recombination). The angle under which we see these patches determines the distance to the surface of last scattering. ($z = z_{\rm dec} \simeq 1100$), $d = r/\theta_p$.
The amplitude of the peaks depends on the matter density ($h = H_0/100$km/s/Mpc)

$$\rho_m \propto \Omega_m h^2 = 0.1417 \pm 0.00097$$

and the difference of the amplitude of even and odd peaks depends strongly on the density of electrons and hence baryons,

$$\rho_b \propto \Omega_b h^2 = 0.02230 \pm 0.00014 \ll \Omega_m h^2$$

Most of the matter in the Universe is dark and non-baryonic!



The cosmic microwave background: parameters from Planck (2015)

The angle subtended by the 1st peak is (together with the CMB temperature) the best measured number in cosmology,

$$\theta_s = \frac{r_s}{d_A(z_s)} = (1.04093 \pm 0.00030) \times 10^{-2} \qquad \delta\theta_s/\theta_s = 2.8 \times 10^{-4}$$

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$$r_s = \frac{2h/H_0}{\sqrt{3(1+z_s)r\omega_m}} \log\left(\frac{\sqrt{1+z_s+r} + \sqrt{\frac{(1+z_s)r\omega_r}{\omega_m} + r}}{\sqrt{1+z_s}\left(1+\sqrt{\frac{r\omega_r}{\omega_m}}\right)} \right), \qquad r = \frac{3\omega_b}{4\omega_\gamma}.$$

$(\Omega_x h^2 \equiv \omega_x)$

$$r_s = (144.81 \pm 0.24)\text{Mpc}.$$

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If $K = 0$,

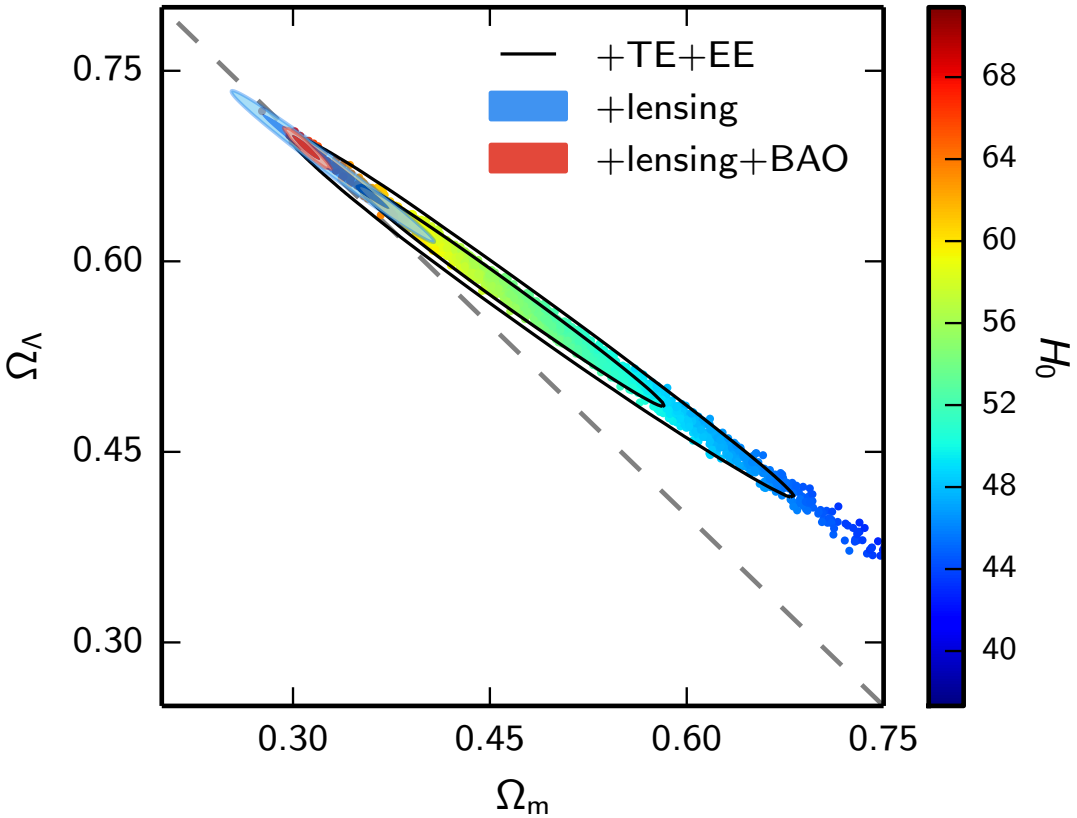
$$\frac{r_s}{\theta_s} = d_A(z_s) = \int_0^{z_s} \frac{dz}{H(z)} = \frac{1}{H_0} \int_0^{z_s} \frac{dz}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}}$$

$$H_0 = (67.74 \pm 0.46)\ \text{km/s/Mpc}$$

(Local measurements find $H_0 = (73 \pm 1.5)$km/s/Mpc, Riess et al. 2016)

The cosmic microwave background: parameters from Planck (2015)

Combining CMB temperature anisotropies, polarisation and lensing breaks degeneracies.

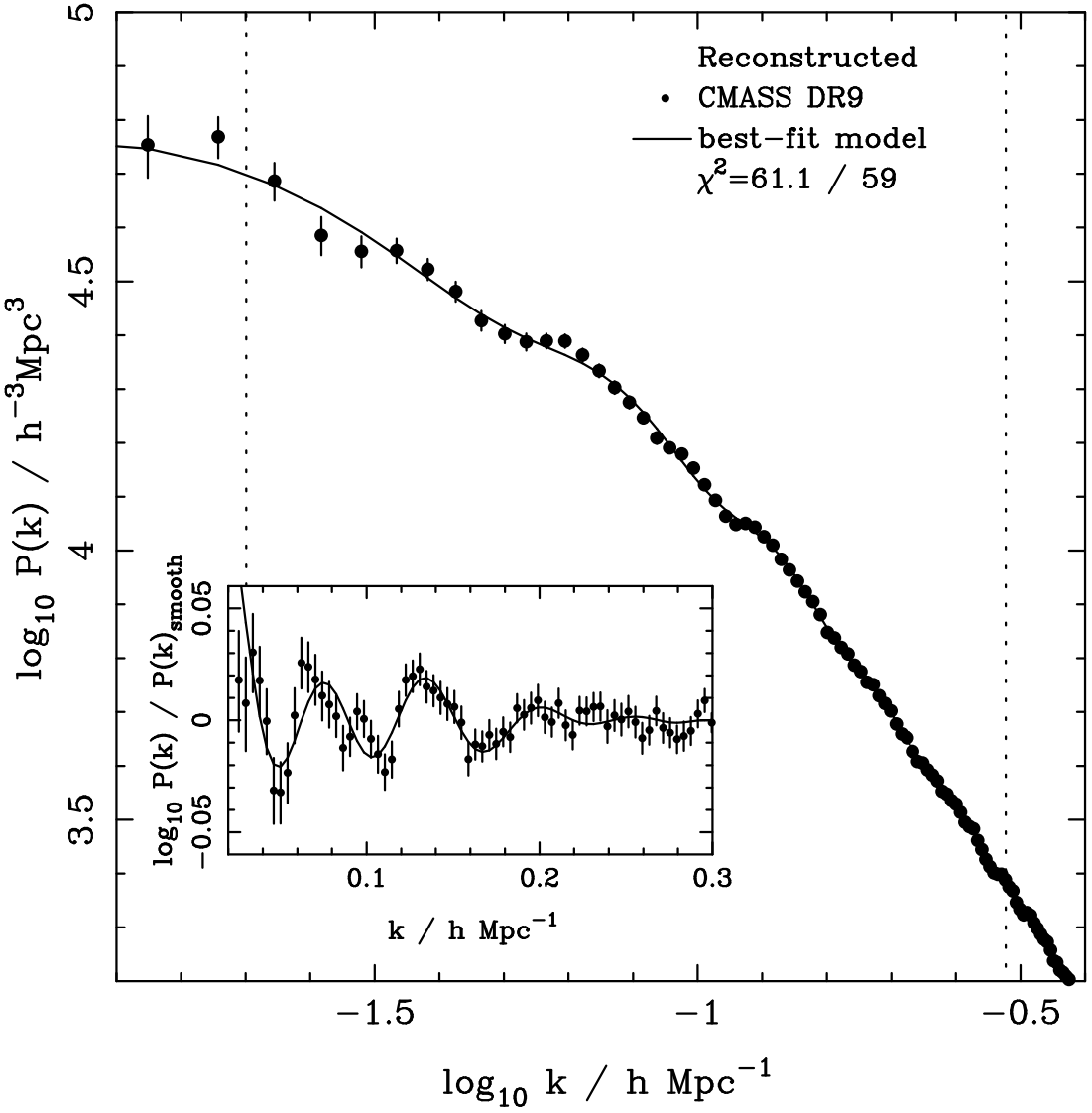


(Planck 2015)

$$\Omega_K = 0.000 \pm 0.005 \qquad \text{at } 95\%$$

Baryon acoustic oscillations

The acoustic peaks are also visible in the matter power spectrum. (= The mean square amplitude of fluctuations of a given size.)



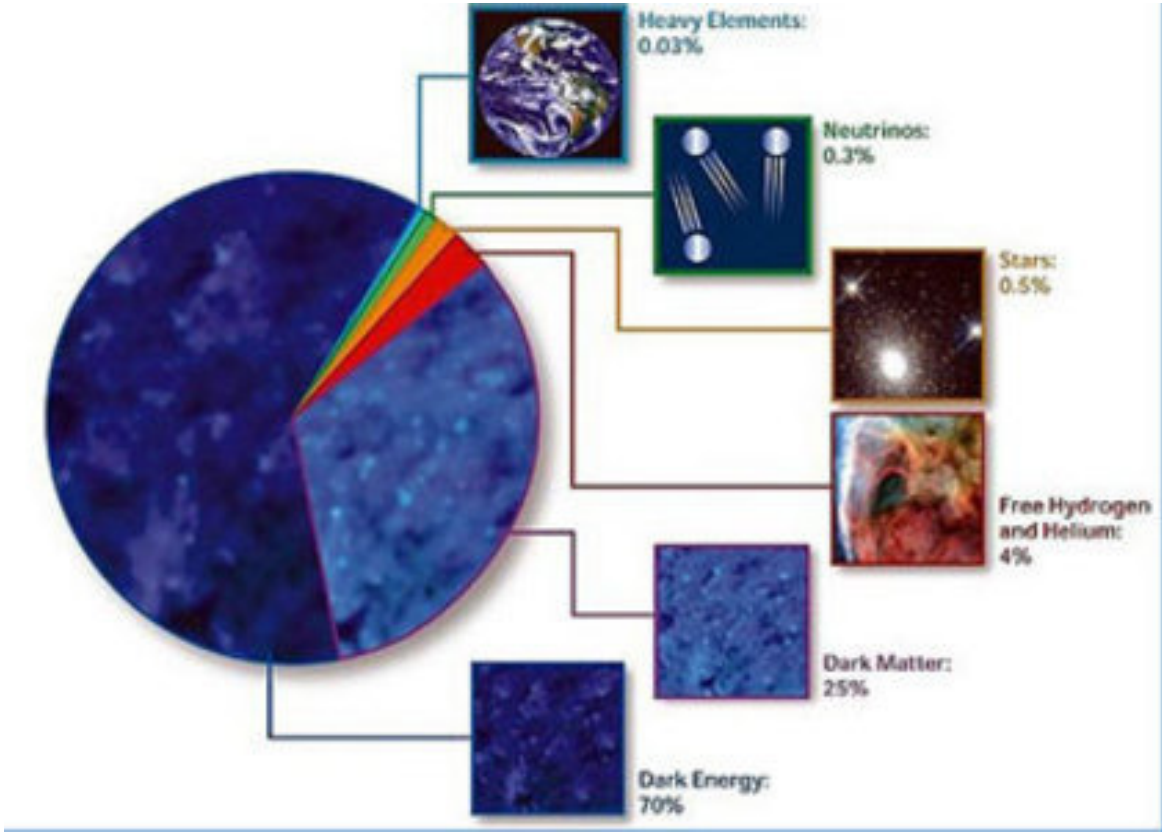
from Anderson et al. '12

SDSS-III (BOSS) power spectrum.

$H_0 = (68.11 \pm 0.86)$km/s/Mpc

(Cheng & Huang, 2014)

The cosmological composition



Data: CMB + BAO + SN Ia

$$
\begin{aligned}
H_0 &= (67.7 \pm 0.5)\text{km/s/Mpc} \\
&= h100\text{km/s/Mpc} \\
\Omega_m &= 0.3 \pm 0.01 \\
\Omega_b h^2 &= 0.0223 \pm 0.00016 \\
\Omega_K &= 0.00 \pm 0.005 \quad (95\%) \\
\Omega_\Lambda &= 0.7 \pm 0.01 \\
\Omega_{\text{rad}} h^2 &= 0.48 \times 10^{-5} \\
\text{age} &= (13.81 \pm 0.026)\text{Gyr}
\end{aligned}
$$

Dark matter

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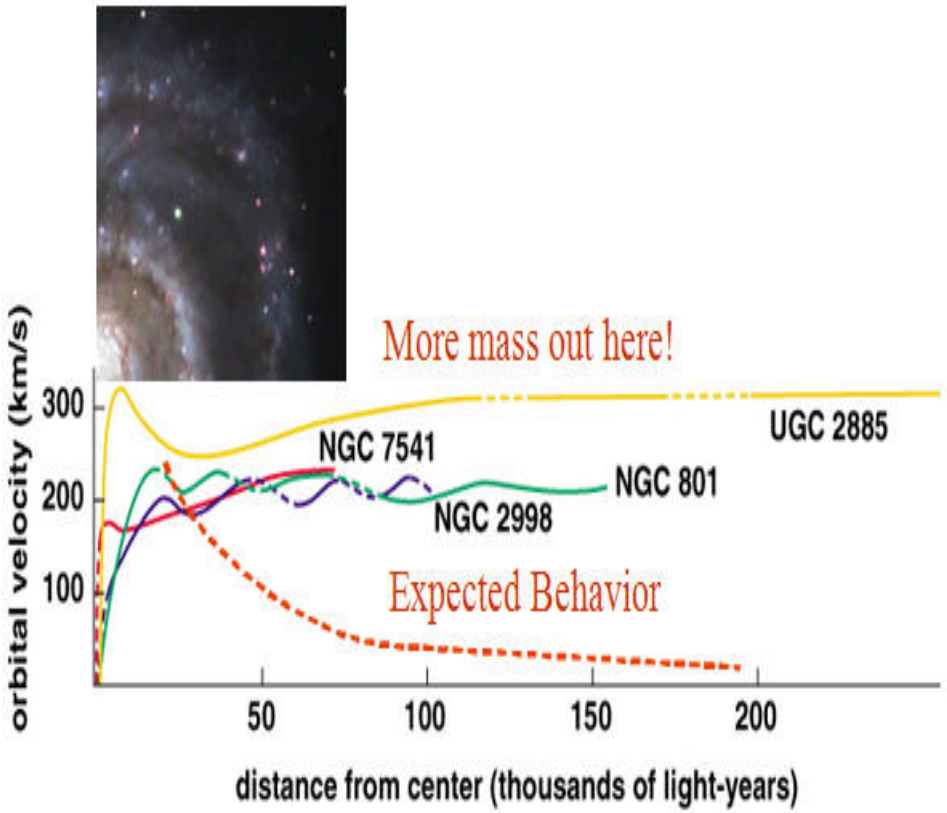
- Also most of the baryonic matter is in the form of gas which does not emit visible light.
- The first to postulate dark matter was the Swiss astronomer Fritz Zwicky. He realized that binding galaxy clusters gravitationally, requires about 100 times more mass than the mass of all its stars (HPA, 1933).
- In the 70ties, the American astronomer Vera Rubin has shown that also galaxies are dominated by dark matter which contributes about 10 times more to their mass than the stars.

Dark matter

Rubin found that the rotation curves of test particles (stars, hydrogen atoms) rotating around galaxies do not show the expected decay of the velocity,

$$v^2 = \frac{GM}{r}, \quad v \propto \frac{1}{\sqrt{r}}$$

but have $v =$ constant. Kepler's law then requires that $M \propto r$.



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- CMB anisotropies (and nucleosynthesis) require $\Omega_b h^2 \simeq 0.02$
- Hence most of dark matter (env. 85%) is non-baryonic.

Dark matter : Candidates

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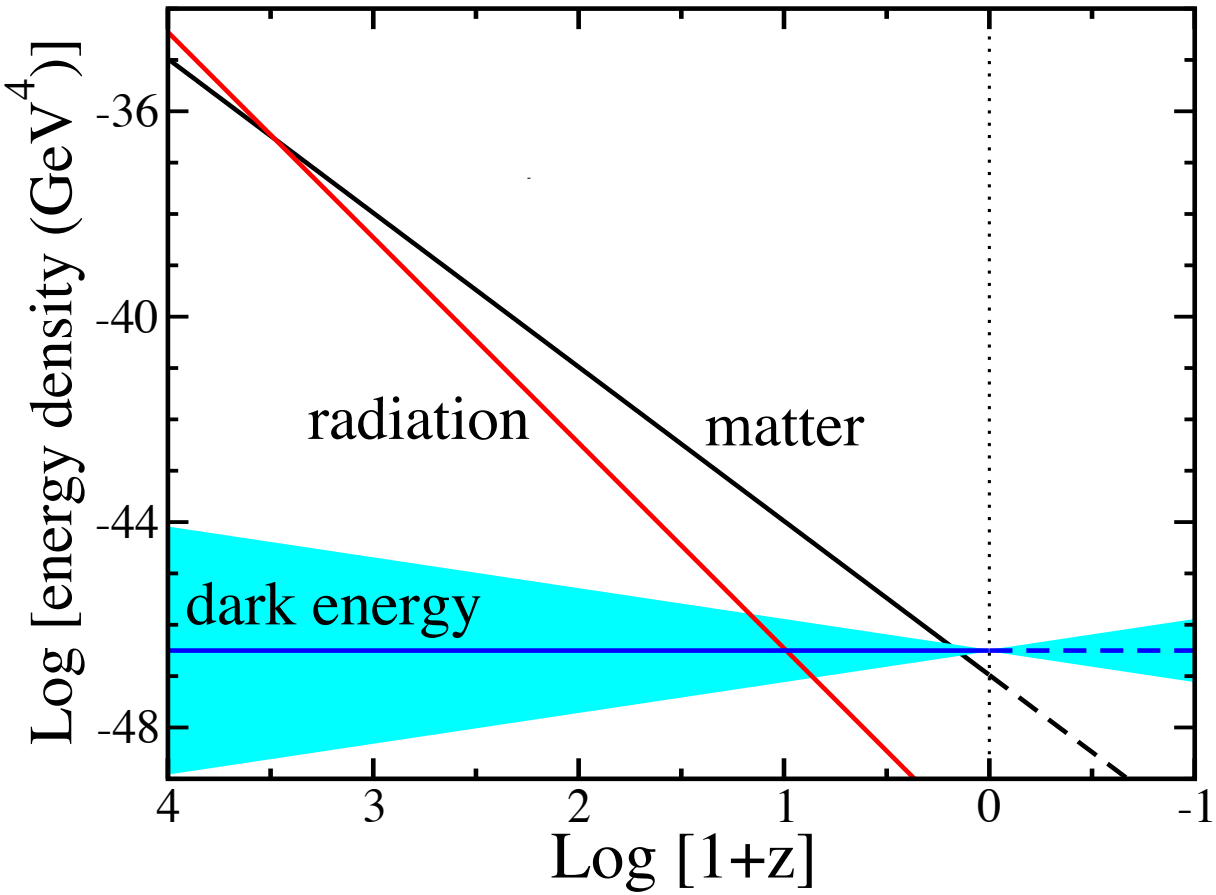
All these candidates require physics beyond the standard model!

Dark energy models

- Cosmological constant / vacuum energy
  Provides a good fit to the data, but nobody understands its value and which it comes to dominate exactly 'now'.



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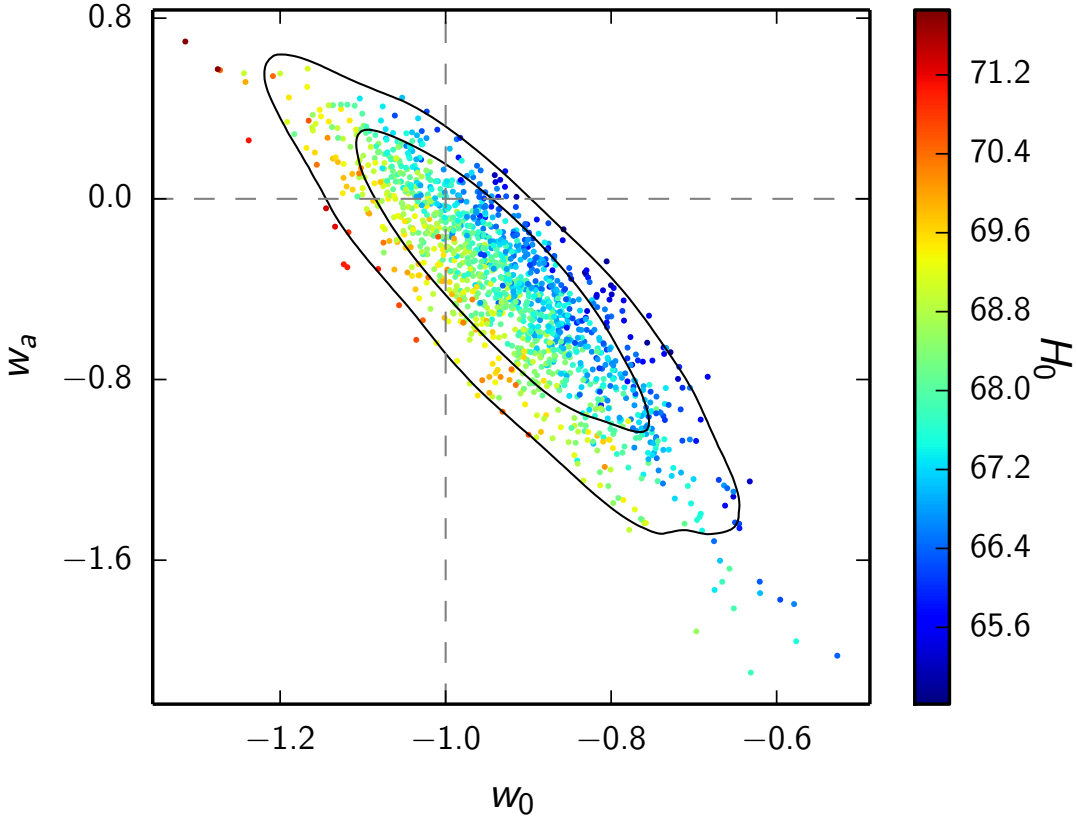

$w = P/\rho_E = -1 \pm 0.08$
=pressure/(energy density)

$w(z) = w_0 + \frac{z}{1+z} w_a$

Planck (2015)

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- Backreaction: If structure formation leads to relevant modifications of the geometry, this could modify the relation between distance and redshift...

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  Only about 5% of the energy density of the present Universe is in the form of matter as we find it in our solar system, ordinary atoms made out of baryons and electrons.